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PARTICLE-WALL INTERACTIONS IN ENTRAINED-FLOW SLAGGING GASIFIERS

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Abstract
This paper aimed at the development of a phenomenological model of the fate of coal/ash particles in entrained-flow slagging coal gasifiers, which considers the establishment of a particle segregated phase in the near-wall region of the gasifier. In particular, near-wall phenomena were investigated and mechanistic understanding of particle–wall interaction patterns in entrained-flow gasifiers was pursued using the tool of physical modeling. Montan wax was used to mimic, at atmospheric conditions, particle-wall interactions relevant in entrained-flow gasifiers. As a matter of fact, this wax had rheological/mechanical properties resembling under molten state, those of a typical coal slag and, under solid state, those of char particles. Experiments have been carried out in a lab-scale cold entrained-flow reactor, equipped with a nozzle whence molten wax atomized into a mainstream of air to simulate the near-wall fate of char/ash particles in a real hot environment. The four particle-wall interaction regimes were investigated. The partitioning of the wax droplets/particles into the different phases was characterized by their selective collection at the reactor exhaust. Results showed that the particle–wall interaction mechanisms and segregation patterns are deeply affected by the stickiness of both the wall layer and the impinging particle. In particular, the micromechanical interaction of a particle with a sticky wall enhances particle transport to the wall and the tendency to reach a segregation–coverage regime with the formation of a dense-dispersed phase in the near-wall region of the reactor. Furthermore, increasing the mainstream air flow rate induces particle segregation and accumulation phenomena.

1. Introduction
The slagging conditions establishing during combustion/gasification of solid fuels play a key role in the design of modern entrained-flow reactors. The residence time in these processes is short (a few seconds), hence, high temperatures are required to ensure a good conversion; for this reason, almost all the entrained-flow gasifiers operate in the slagging mode. These operating temperatures ensure the destruction

of tars and oils and, if the gasifier is appropriately designed and operated, a very high carbon conversion may be reached [1].
The slagging behavior of ash plays a key role in the performance of entrained-flow gasifiers. At temperatures above the ash-softening point, the ash becomes sticky and agglomerates, causing blockage of the beds or fouling of the heat exchange equipment. Once above the slagging temperature (about 1300-1500°C), ash has a fully liquid behavior with a relatively low viscosity, hence, it is possible to remove it from the system. Entrained-flow gasifiers have become the preferred technology for hard coals, and have been selected for the majority of commercial-sized IGCC applications. One advantage of a slagging reactor over a non-slagging combustor is the fact that the collected slag has in general a higher economic value compared with the bottom ash, because of its longer durability and resistance to surface wear. In addition, the slag layer results in a molten protective coating and reduces the heat loss to the wall, generally increasing the cold gas efficiency of the gasifier [2]. However, the increasing slag layer can bring about gasifier plugging, and the slag deposition on the wall membrane reduces the overall heat-transfer coefficient. The molten ash flows through the bottom of the gasifier and is quenched in a water bath [3]. The collected slag may have a relatively large content of unburned carbon. The presence of unburned carbon is a result of the incomplete gasification of the coal, which is the major determinant of the gasification efficiency in entrained-flow processes. The carbon content in fine and coarse slags can reach 60% and 30–35% respectively [4], and this is a crucial key also in coal gasification modeling. Char and ash particle deposition flux depends on the flow field and char trajectories, wall temperature, as well as on char properties such as carbon conversion, ash composition, particle diameter and velocity. Furthermore, the extent of coverage of the slag layer by carbon particles must also be taken into account given the relevance of the stiffness and surface roughness to the micromechanics of a particle impinging a refractory wall, a layer of adhered particles, or a layer of molten slag. The extent of surface coverage by carbon particles is governed by carbon impingement on the slag layer, convective transport of flowing slag, and gasification of carbon deposited on the slag. Different near-wall carbon-slag segregation regimes (*entrapment*, *segregation*, *segregation–coverage*) can occur [5], as a function of the reactor axial coordinate and of the progress of X_C. Also local hydrodynamic conditions influence the particle–wall interaction and, thus, the extent of carbon coverage onto the slag layer. Micromechanical interaction patterns and local hydrodynamics can determine the contributions of ash and slag within the gasifier. Particle–wall interaction occurs according to different micromechanical patterns, which depend on parameters such as particle and wall temperatures, solid/molten status of the particles and wall layer, char conversion degree, particle kinetic energy, surface tension of the slag layer, particle effective stiffness and char/slag interfacial tension. Char–slag interaction patterns are hereby classified on the basis of the *stickiness degree* of the wall layer and of the impinging char particle:

- the material laying on the wall (prevailingly, inorganic ash) is *sticky* when the wall temperature is high enough to ensure an ash molten status, generating a liquid slag layer. An additional condition for the slag layer to be sticky is that it must not be extensively covered by *non sticky* char particles;
- the char particle is sticky when its temperature is beyond the ash melting point, and its carbon conversion degree is beyond a given threshold value, as the plastic behaviour is emphasized when the carbon content, which is inherently refractory, is reduced.

On the basis of this classification, four interaction scenarios establishing during EF gasification can be considered, namely: *(i)* non sticky char/ash particle impinging on a molten-slag-covered sticky wall (*NSP–SW*); *(ii)* non sticky char/ash particles impinging on a non sticky wall (*NSP–NSW*); *(iii)* molten, i.e. sticky, ash particles impinging on a non sticky wall (*SP–NSW*); *(iv)* molten sticky ash particles impinging on a sticky wall (*SP–SW*).
This study aims at investigating near-wall particle segregation by using a lab-scale cold entrained-flow reactor. The cold flow model reactor ensures the formation of a dispersed phase and a near-wall layer to reproduce and characterize the four micromechanical interaction patterns.

2. Experimental

A lab-scale cold flow model reactor has been designed and set up, aiming at reproducing the basic general features of the interaction between a lean-dispersed particle/droplet phase and a confining wall. The model reactor is outlined in Fig. 1.

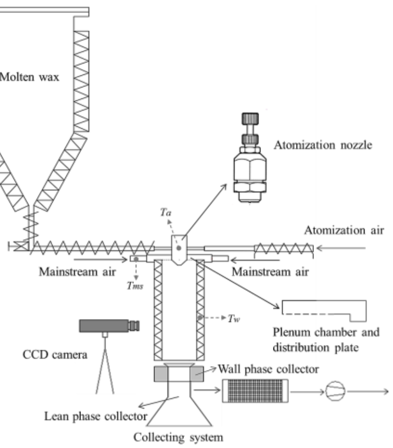

Figure 1. Experimental apparatus.

The plastic/fluid behaviour of softened or molten ash and of the wall slag layer has been simulated, at nearly ambient conditions, by molten wax as a surrogate of fuel ash. Waradur E^{TM} (Völpker Spezialprodukte, Germany) was selected, as the rheological/mechanical properties of this wax (a refined material made from black

raw montan wax) resembled those of a typical coal slag [6,7]. Wax properties are such that the entrapment and over-layering criteria are not satisfied, and the segregation or segregation–coverage regimes are likely to be established, as expected for realistic particle–slag interaction in entrained-flow gasifiers [5]. Moreover, mechanical properties of solid wax well agree with data for coal/char, confirming the suitability of this wax to mimic also the char behavior [8]. Details on the experimental apparatus and operation are described elsewhere [7].
In order to correctly operate the lab-scale reactor, three different temperatures have to be taken in account: the atomization temperature (T_a), i.e. the nozzle exit temperature, the main stream temperature, the wall temperature. Tuning these three temperatures, it is possible to obtain the different interaction regimes. Experimental tests aimed at characterizing the phenomenology of the interaction between the dispersed phase generated by the spray and the reactor walls. The operating conditions were selected so as to reproduce the four possible regimes (*SW–SP*, *NSW–NSP*, *NSW–SP*, *SW–NSP*), and are listed in Table 1. The values of Q_a complied with the nozzle constraints and assured good wax atomization in terms of size and dispersion of droplets for all the investigated regimes.

Table 1. Main reactor design and operating parameters.

	SW–SP	***NSW–NSP***	***NSW–SP***	***SW–NSP***
Reactor internal diameter D [m]	0.1	0.1	0.1	0.1
Reactor length L [m]	0.1–0.6	0.1–0.45	0.1–0.6	0.15–0.6
Atomization temperature T_a [°C]	110	100	120	100
Mainstream temperature T_{ms} [°C]	160	30	90	30
Wall temperature T_w [°C]	140	30	30	110–190
Wax feeding rate W_{wax}^{lean} (z=0) [g s^{-1}]	0.6	0.2–0.3	1	0.2–0.3
Flow rate of mainstream air Q_{ms} [m^3 h^{-1} at 273 K]	1–5	1–20	1–10	2–10
Flow rate of atomization air Q_a [m^3 h^{-1} at 273 K]	0.275	0.275–0.8	0.275	0.5

The reactor length L was varied to study the influence of the distance from the injection nozzle on the fractional mass of wax transferred form the lean-dispersed phase to the wall layer. Reactor ducts of different lengths were used for this purpose. Partitioning measurements of the atomized wax between the dispersed and the wall phases were quantitatively assessed. To accomplish this task, the reactor was equipped with a system (consisting by a vacuum flask, a trap, a filter and a pump) for the two phases wax collection at the bottom of the Pyrex tube. The mass flow rates in the dispersed phase and in the wall layer phase were obtained by dividing the amounts of wax cumulatively collected by the duration of the test.

3. Results and Discussion

In the following figures, the experimental data are reported as average values of multiple tests (symbols), together with error bars corresponding to the standard deviation. The effect of the mainstream air flow rate (Q_{ms}) on the partitioning of wax is reported and discussed. The partitioning of the atomized wax between the dispersed and the wall phases as a function of the distance from the nozzle is reported in Fig. 2a) for all the interaction regimes, at fixed Q_{ms} (1 $m^3 h^{-1}$ for *SW-–SP*, *NSW–SP* and *NSW–NSP* regimes, 2 $m^3 h^{-1}$ for the *SW–NSP* regime). y^{lean} reaches maximum values for the *NSW–NSP* regime, minimum values for the *SW–SP* regime, while its values in the *SW–NSP* regime lie between those for the *NSW–NSP* and *NSW–SP* regimes, as expected. As a matter of fact, the interaction of a non sticky particle with a liquid layer can lead to segregation and segregation–coverage regimes. Therefore, the fractional content of wax in the lean-dispersed phase is lower than that obtained in the *NSW–NSP* regime. On the other hand, the interaction of the particles with the liquid layer and with other particles makes the fractional content of wax in the lean phase larger than that obtained for the *NSW–SP* and *SW–SP* regimes, for which the main interaction pattern is the deposition. Figure 2b) reports the partitioning of the atomized wax between the dispersed and the wall phases, as a function of the distance from the nozzle for the *NSW–SP*, *NSW–NSP* and *SW–NSP* regimes, at fixed Q_{ms}=10 $m^3 h^{-1}$. The values of y^{lean} are lower for all the investigated regimes (compared to the results shown in Fig. 2a)). Data points obtained in the *SW–NSP* regime are very close to those obtained in the *NSW–SP* regime.

On the whole, it is possible to conclude that sticky particles mainly adhere on the wall surface, regardless the stickiness of the wall, whereas non sticky particles may rebound, deposit, segregate and be resuspended into the main gaseous flow. As regards the interaction of non sticky particles with a sticky wall, the partitioning results lie between those obtained for the other regimes, indicating that a dense-dispersed phase in the near-wall region of the reactor may establish. Larger mainstream air flow rates reduce the fractional content of wax in the dispersed phase, enhancing particle deposition/segregation phenomena in the *NSW–NSP* regime, and less markedly in the *SW–NSP* regime. This result was explained by considering the interaction between the mainstream flow and the oblique stagnation flow typical of the outer jet. Increasing the mainstream rate moderates the stagnation effects and suppresses the local turbulence, which is largely responsible for particle resuspension and rebound, thus favoring the stratification and segregation of particles in the near-wall region of the duct.

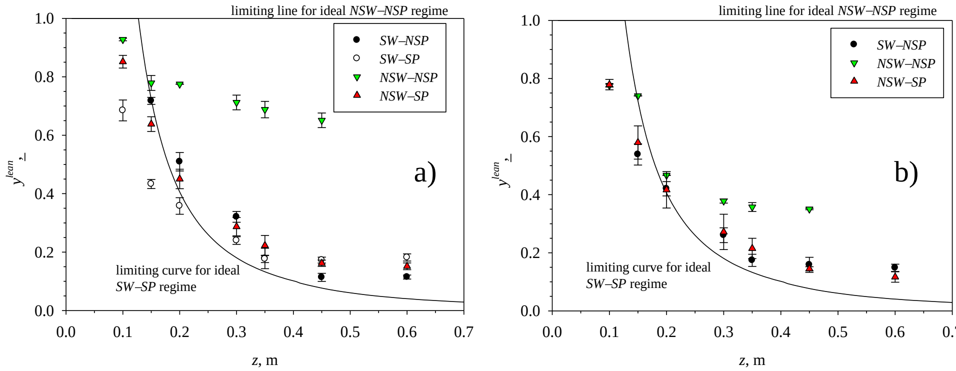

Figure 2. Partitioning of wax for all the interaction regimes. a) Q_{ms}=1–2 m^3 h^{-1}; b) Q_{ms}=10 m^3 h^{-1}. The limiting curves representing the *NSW–NSP* and the *SW–SP* regimes are plotted as a reference.

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doi: 10.4405/38proci2015.VI2